TeV OBSERVATIONS OF THE VARIABILITY AND SPECTRUM OF MARKARIAN 501

J. Quinn[1,2], I.H. Bond[3], P.J. Boyle[2], J.H. Buckley[1], S.M. Bradbury[3], A.C. Breslin[2], A.M. Burdett[3], J. Bussons Gordo[2], D.A. Carter-Lewis[4], M. Catanese[4], M.F. Cawley[5], D.J. Fegan[2], J.P. Finley[6], J.A. Gaidos[6], A. Hall[6], A.M. Hillas[3], F. Krennrich[4], R.C. Lamb[7], R,W. Lessard[6], C. Masterson[2], J.E. McEnery[2], G. Mohanty[4], P. Moriarty[8], A.J. Rodgers[3], H.J. Rose[3], F.W. Samuelson[4], G.H. Sembroski[6], R. Srinivasan[6], T.C. Weekes[1] and J. Zweerink[4]

[1]*Whipple Observatory, Harvard-Smithsonian CfA, Box 97, Amado, AZ 85645, U.S.A.*
[2]*Dept. of Experimental Physics, University College, Belfield, Dublin 4, Ireland*
[3]*Physics Dept., University of Leeds, Leeds, LS2 9JT, Yorkshire, U.K.*
[4]*Dept. of Physics and Astronomy, Iowa State University, Ames, IA 50011-3160, U.S.A.*
[5]*Physics Dept., St. Patricks College, Maynooth, Ireland*
[6]*Dept. of Physics, Purdue University, West Lafayette, IN 47907, U.S.A.*
[7]*Space Radiation Lab., Caltech, Pasadena, CA 91125*
[8]*Dept. of Physical Sciences, Regional Technical College, Galway, Ireland*

ABSTRACT

Markarian 501 is only the second extragalactic source to be detected with high statistical certainty at TeV energies; it is similar in many ways to Markarian 421. The Whipple Observatory gamma-ray telescope has been used to observe the AGN Markarian 501 in 1996 and 1997, the years subsequent to its initial detection. The apparent variability on the one-day time-scale observed in TeV gamma rays in 1995 is confirmed and compared with the variability in Markarian 421. Observations at X-ray and optical wavelengths from 1997 are also presented.

INTRODUCTION

Markarian 501 was discovered as a γ-ray source by the Whipple Collaboration in 1995 (Quinn, et al., 1996) and has since been verified by the HEGRA Collaboration (Bradbury et al., 1997). At the time of its discovery the average emission level was 0.08 times that of the Crab Nebula. During 1995 the γ-ray emission from Markarian 501 was observed to be constant, with the exception of one occasion where the emission level rose to more than 5 standard deviations above the average rate. Within 2 days the rate had returned to its average level. This day-scale variability is also seen in Markarian 421 (Kerrick et al., 1995). Markarian 501 is also seen to vary at X-ray energies on time-scales from months (Mufson et al., 1984) to hours (Giommi et al., 1990), and at optical wavelengths significant variations as short as hours have been observed (Kidger & de Diego, 1992). The results of continuing γ-ray observations made by the Whipple Collaboration in 1996 and 1997 are presented below. Also presented are X-ray data from the All-Sky Monitor of the Rossi X-ray Timing Explorer (2-10 keV) and optical data taken (U-band) with the 1.2m telescope of the Whipple Observatory during 1997.

The γ-ray observations reported in this paper were made with the 10m Atmospheric Čerenkov Imaging Telescope of the Whipple Collaboration, which operates at an energy threshold of 350 GeV. The telescope records images of the Čerenkov radiation emitted from cosmic ray initiated air-showers with a high resolution camera consisting of a hexagonal array of photomultiplier tubes. Subsequent analysis of the images determine which were probable γ-ray events (Reynolds et al., 1993). Using this technique it is possible to reject over 99.7% of the background while retaining over 50% of the γ-ray events. The camera has recently been upgraded from 109 to 151 pixels (increasing the field of view from 3.0° to 3.5°) and the γ-ray selection criteria were re-optimised to take advantage of this. Therefore, to meaningfully compare the data taken over the last 3 years the γ-ray rates are expressed as a fraction of the rate from the Crab Nebula, which is a steady source of TeV γ-rays (Hillas et al.,

investigations suggest is true (see below).

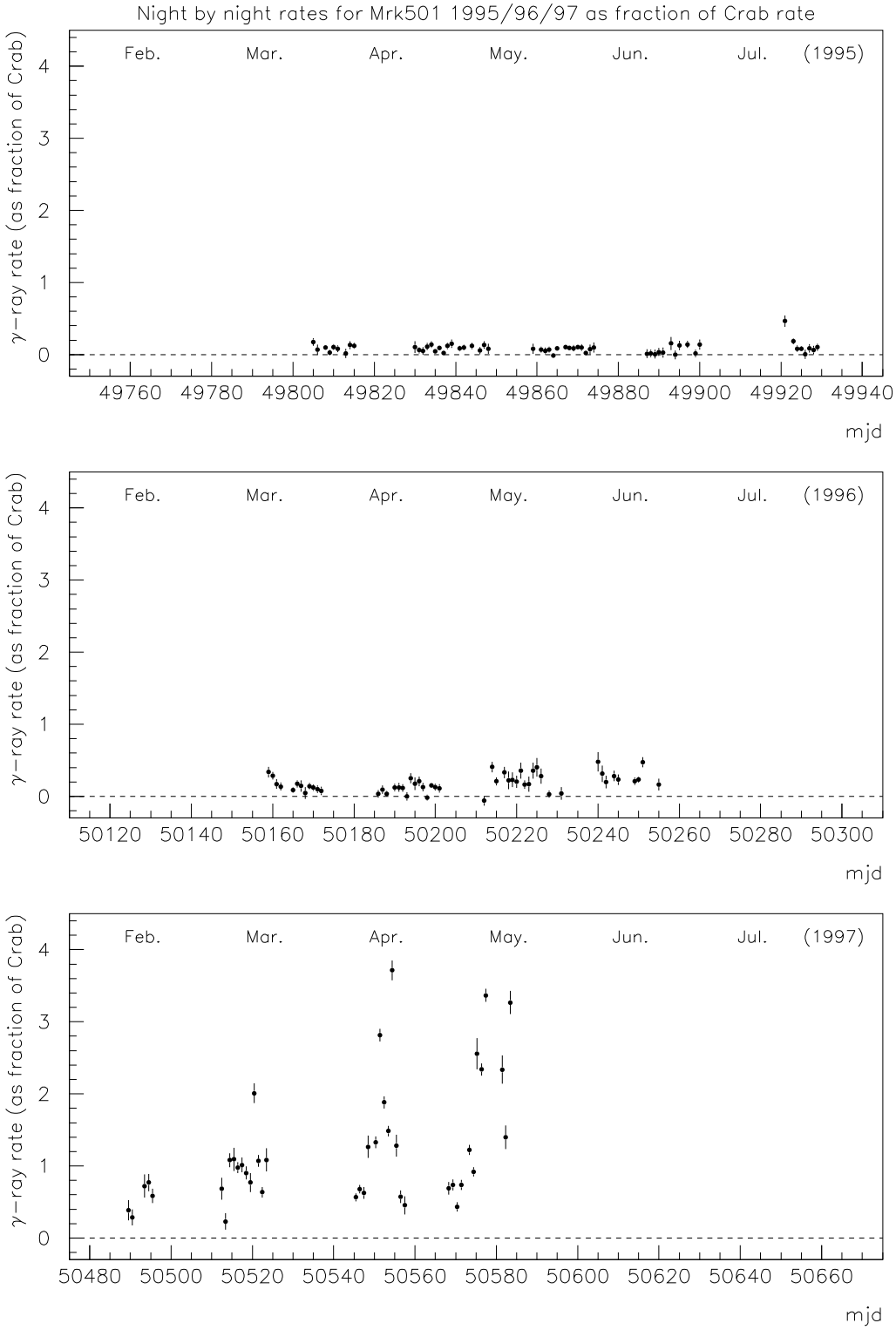

Fig. 1: Daily γ-ray rates for Markarian 501 for last 3 years, expressed as fraction of average rate from Crab Nebula.

GAMMA-RAY FLUX VARIABILITY

Figure 1 shows the nightly flux levels for Markarian 501 for the 3 years of observations, up to and including May 1997. A subset of the 1997 data is also shown in figure 2(a). As already stated, Markarian 501 exhibited variability on times-scales of $\sim$1 day during 1995. The χ^2 probability for the

Observations in 1996 showed a doubling in the average emission level, increasing from 0.08 times to 0.16 times that of the average Crab level. There was no obvious flaring activity, although the night-to-night rate did appear to be less stable. The χ^2 probability for constant emission for this year is 10^{-12}, indicating that there is variation on the scale of days. The low signal-to-noise levels in these data do not permit the search for variability on shorter time-scales.

A remarkable change in the γ-ray emission was seen in 1997: the rate increased dramatically from previous seasons, the average now being almost 1.3 times that of the Crab. There is also significant and frequent flaring activity. On several occasions (May 12-13, April 12-13, April 15-16 and May 14-15) there have been flares with doubling times of less than one day. The χ^2 probability for constant emission is $<10^{-38}$ for this data while for Crab Nebula data taken in 1997 it is 0.95. A preliminary analysis did not reveal evidence for variability on time-scales less than 1 day, but a more detailed study is underway.

MULTI-WAVELENGTH OBSERVATIONS IN 1997

In figure 2, flux measurements at VHE γ-ray, X-ray and optical are presented. The X-ray data is taken from the Rossi X-ray Timing Explorer (RXTE) All Sky Monitor data-set. It appears from this data that Mrk501 is in a particularly active state, with a flux higher than in previous years. The significance of the apparent variations around the time of the April (MJD 50540 to 50560) γ-ray data has not yet been established, nor has a correlation analysis been performed. The optical data was taken with the 1.2m telescope located at the Whipple Observatory. For a more detailed review of the optical data see Buckley & McEnery (1997). The flux (U-band) shows a significant increase ($\gtrsim$ 10%) from March to April while it appears to continue to increase during April.

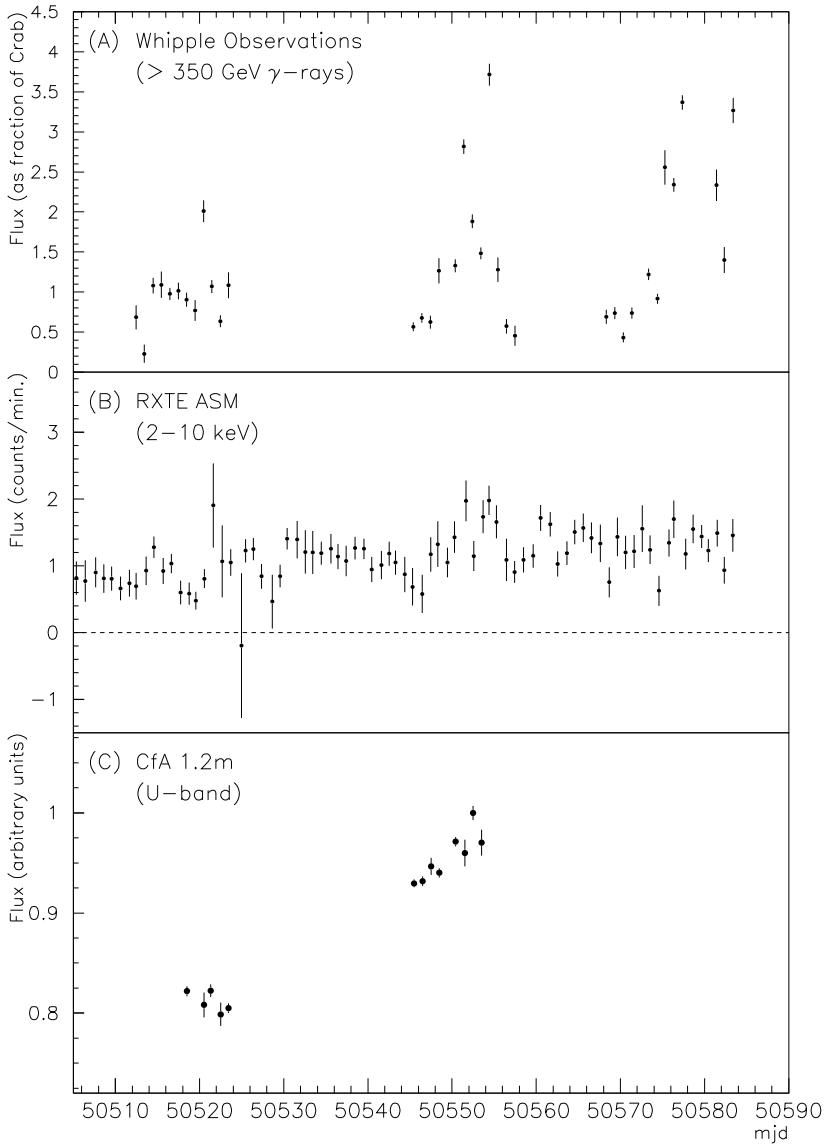

Fig. 2: Multi-wavelength observations of Markarian 501 in 1997: (a) Whipple (> 300 GeV) γ-rays, (b) RXTE All Sky Monitor and (c) 1.2m CfA (U-band).

ENERGY SPECTRUM

A spectral analysis of the 1997 Markarian 501 data, using the method of Mohanty (1997) is currently under way and details will be presented at this conference. However, it is possible to get an indication of how

an image) distributions of the candidate γ-ray events. The method of Vacanti et al. (1991) was used to calculate the size spectra and preliminary results indicate that the spectrum of Markarian 501 may be slightly harder than that of the Crab Nebula; the spectra are not, however, significantly different when systematic effects are taken into consideration. Large zenith angle observations indicate that the spectrum extends out to at least 7 TeV (Krennrich, 1997).

DISCUSSION

A remarkable change in the TeV γ-ray emission from Markarian 501 has been seen in 1997. The average emission level has increased by a factor of more than 16 since its discovery as a γ-ray source in 1995. Day-scale variability, as we have seen on one occasion in 1995, has been confirmed and the frequency of the flaring appears to have increased. Day-scale variability is a property which Markarian 501 has in common with Markarian 421 (Buckley et al., 1996). However, preliminary analysis of the data does not reveal any evidence for hour-scale variability, as is seen in Markarian 421 (Gaidos et al., 1996). The γ-ray emission from Markarian 501 rarely goes to zero, in contrast to Markarian 421, whose flux has been described as being composed of a series of rapid flares, with no underlying baseline emission (Buckley et al., 1996). Detailed analyses to search for short ($<$ one day) term variability, to determine an energy spectrum and to look for possible correlations with other wavelength data are currently underway.

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